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The Effect of Para-Ortho Shift on Heat Exchanger Design in Hydrogen Nitrogen Heat Exchange at High Pressures

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MATERIALS CENTRAL

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The Effect of Para-Ortho Shift on Heat Exchanger Design in Hydrogen Nitrogen Heat Exchange at High Pressures

James H. L. Lawler

Materials Central

December 1960

Project 3048

Wright Air Development Division
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

AF-EGLIN AFB FLA

FOREWORD

This technical note was prepared under Project 3048, ''Aviation Fuels,'' and Task 30193, ''High Energy Fuels,'' by James H.L. Lawler of the Fuels Section, Fuels and Lubrication Branch, Applications Laboratory, Materials Central, Wright Air Development Division. It was prepared largely from data included in the National Bureau of Standards' Report RP 1932, and data from the Cambridge Corporation, the latter being used as a check.

This note covers work for the period May 1960 to June 1960.

ABSTRACT

The effect of para-ortho shift is found on heat exchanger design by calculating heat exchanger sizes for several hydrogen to nitrogen flow ratios. This calculation shows that size is exponential to a limit when plotted against lbs of H_2 / lbs of N_2 (#H_2) flow and that para-ortho shift has a pronounced effect above 5#H_2/#N_2.

PUBLICATION REVIEW

This Technical Note has been reviewed and is approved.

FOR THE COMMANDER:

L.C. Dickey

L.C. DICKEY
Ass't. Chief, Fuels & Lubrication Branch
Applications Laboratory
Materials Central

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INTRODUCTION

The purpose of these calculations is to evaluate the effect of para-ortho shift on the heat exchanger size when using hydrogen as a condensing media for nitrogen.

DISCUSSION OF METHODS AND RESULTS

The Newtonian heat exchanger equation ($Q = UA\Delta T$) was assumed as a basis for calculations, where Q = heat flow, U = overall heat transfer coefficient, A = area, and ΔT = change in temperature.

As a first approximation normal hydrogen was assumed to have the same specific heat (Cp) as para hydrogen, and the total ΔQ was found for normal hydrogen to nitrogen heat exchange and for a normal hydrogen plus heat of conversion (of para to ortho hydrogen) to nitrogen heat exchanger. This is found in Appendix I in detail.

It must be realized that the normal hydrogen curve is valid; however, the normal hydrogen plus a heat of conversion curve is artificial and has no real meaning. The artificiality is useful, however, to predict the difference between para and equilibrium hydrogen curves. This is found and justified later by comparison with the calculated para curves.

The enthalpy of para hydrogen was calculated from normal hydrogen data and heats of conversion. This is shown in Appendix I, figures 12 and 13.

From the calculated enthalpy of para hydrogen the size of para hydrogen and para hydrogen plus heat of conversion to nitrogen heat exchangers were calculated. The results are shown in the Appendix I.

The size of the H_2 - N_2 heat exchanger is found to be an exponential function with a limit when plotted vs flow ratio of $\#N_2/\#H_2$ as shown in Figures 4, 5, 6, 14, and 15.

The effect of para-ortho shift is shown in Figures 7, 16 and 17 and becomes quite important above a flow ratio of $5\#N_2/\#H_2$.

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The effect of nitrogen pressure variations is shown in Figure 11 of Appendix I.

A sample calculation of a heat exchanger weight is made in Appendix II.

The difference between normal H_2 plus heat of conversion and para hydrogen is shown in Figure 16.

CONCLUSIONS

The size of a H_2-N_2 heat exchanger condenser is exponentially a function of flow ratio of $\#N_2/\#H_2$. This is in agreement with the literature. The function is such that at 800 psia hydrogen and 20 atm (194 psia) or 33.5 atm N_2 being cooled from 300° or 500°R, a straight line assumption is reasonable below the flow ratio of $5\#N_2/\#H_2$. Above this value the assumption is poor.

The effect of hydrogen para-ortho shift on heat exchanger design is small at low ratios of $\#N_2/\#H_2$ up to $3\#N_2/\#H_2$. Above this value it becomes a minor factor and should be considered. Above $5\#N_2/\#H_2$ the para-ortho shift affects the size of an exchange 25 percent or more and is a major factor.

DATA SOURCES

The enthalpy of H_2 was taken from NBS RP 1932 and Cambridge Corporation Data.

N_2 enthalpy was taken from WADC TR 59-8, Cryogenic Data Book.

The para-ortho data is taken from Scott's "Cryogenic Engineering" and NBS RP 1932.

The U is taken from WADC TR 59-422, the final report of AiResearch Products, Inc., under Contract AF 33(600)-34222.

APPENDIX I

EXPLANATION OF CHARTS

The calculations are based on the temperature increments at temperatures listed in column 1 in the Table.

The enthalpy of normal hydrogen is taken at 800 psia (54.4 atm) in columns 2 and 3 from the two sources and averaged in column 4. The ΔH for n-H_2 is then found in column 5. Column 6 is the change in enthalpy for each temperature rise of 10, 20, or 50°R as shown in column 1.

Column 7 is the per cent ortho H_2 at equilibrium at each temperature in column 1 from NBS 1932, and column 8 is the heat of conversion at the same temperature from "Cryogenic Engineering;" column 9 is the product of 7 and 8 and is the ΔH of conversion for para H_2.

Column 10 is taken from the plot of the sum of columns 6 and 9 (recorded in column 19) on figure 1.

Column 11 is the enthalpy of N_2 in BTU/mole from Cryogenic Data Book at 20 Atm. Column 12 is the same divided by the molecular weight (28) of N_2. Columns 13 through 18 are the products of column 12 and the constants 2,4,5,6,7, and 8 to represent 2 through 8# of N_2 condensed per #H_2. This is plotted to complete figures 1 and 2.

Column 19 is the sum of columns 9 and 6.

Columns 20, 23, and 26 are taken from figure 1 and represent the temperature difference (ΔT) between nH_2 at the temperature of column 1 and the nitrogen curves.

Columns 29, 32, 35, and 38 are taken at the same enthalpy as columns 20, 23, and 26 but the temperature difference is between para-equilibrium hydrogen and the N_2 curves.

Column UA_1 after the above ΔT is the ΔH change in enthalpy (column 6) divided by the

ΔT and as such is the amount of exchanger necessary to perform the indicated heat exchange. This comes from the relation $Q = UA \Delta T$ where Q is the heat flow and equals ΔH in this case, and ΔT is temperature drop causing the heat flow.

The UA_2 columns are the sum of the UA_1 columns but are more accurate than the sum of the rounded figures in UA_1 since this operation was performed simultaneously with the calculation of UA_1.

Columns 41 and 47 are the same as Columns 12 to 18 but for 33.5 atm N_2.

The data Columns 41 to 47 are plotted in figure 3.

Figures 4 and 5 are the results obtained in the cumulative UA calculations UA_2 for N_2 starting temperature of 300 and 500°R respectively.

Figure 6 was estimated by comparison of figures 1 and 3 with appropriate values entered into figure 4 and then replotted. When figures 1 and 3 are overlaid they allow estimation of $\#N_2/\#H_2$ between the integer values of figure 1 which would have the same ΔT as the plot in figure 3. This value when entered on figure 4 gives fair estimates of the values in figure 6.

Figure 7 is obtained from figures 4 and 6 and represents the effect of para shift on Heat Exchanger UA (which is proportional to size and weight).

Columns 60 to 73 are the data for figures 8 and 9.

Columns 48 to 59 are similar to 20 to 40 but are the data needed to plot figure 10.

Figure 11 is a plot of the effect of pressure on UA at $5\#N_2/\#H_2$ and $6\#N_2/\#H_2$ with and without para-ortho shift.

Column 74 is the heat of conversion if normal hydrogen is converted to para (.75 times column 8).

Column 75 is the total change in 74 and as such is the ΔH of the para-ortho shift. This

value is the number in column 74 subtracted from 228.15 and represents a cumulative difference in Cp.

Column 76 is the sum of 75 and 5 and is a calculated H for para hydrogen. This is plotted in Figures 12 and 13.

Columns 78 through 98 are the recalculations of columns 20 to 40 with the best calculated value of para hydrogen enthalpy. This list is taken into account by additional ΔT as shown in column 77 which is taken from Figures 12 and 13.

APPENDIX II

SUPPLEMENTARY DATA

Sample calculation of heat exchanger weight WADC TR 59-422 lists 2.75 BTU/min ft^2 °R as a reasonable U for H_2 to He heat exchange at a H_2 Reynolds number of 23,900.

This value is probably high for N_2 but since the H_2 could be made to flow more rapidly to compensate, the H_2 to He value has been used in this calculation. Desired parameters: Ratio of Nitrogen flow to Hydrogen flow: 5.6 #N_2/#H_2, N_2 flow rate 2000 #/sec, 3/8 inch aluminum tubing with 1/100 inch wall.

1. H_2 flow #/sec = 2000/5.6 = 357.1 #/sec
2. UA at 5.6 #N_2/#H_2 = 10 (maximum no shift) or 6 (minimum 100% shift)
3. UA is in BTU/°R per # of H_2 basis hence

   $$\frac{(\text{UA BTU/°R } 60 \text{ sec/min}}{2.75 \text{ BTU/ft}^2 \text{ min°R}} = \text{UA } (21.818) \text{ ft}^2/\# \text{ per sec } H_2 \text{ flow}$$

4. A = (UA ft^2/# per sec H_2 flow) (# per sec H_2 flow) (21.818)
   A max = (10) (21.818) (357.1) = 7791.2
   A min = (6) (21.818) (357.1) = 4674.7
5. Area of 3/8 inch tubing is (3/8) π/12 = .098 ft^2/ft of tubing
   (7791.2)/.098 = 795,020 ft of 3/8 tube maximum
   (4674.7)/.098 = 477,010 ft of 3/8 tube minimum
6. Weight of 3/8 inch, 1/100 in wall tube is about (.098 ft^2/ft) (1/100 inch thick) (1/12 ft/inch) = 8.1667 x 10^{-5} ft^3/ft: (8.1667 x 10^{-5} ft^3/ft) (62.4 #/ft^3) (2.7) = 1.376 x 10^{-2} #/ft of tubing
7. 795,020 ft max (1.376 x 10^{-2} #/ft) = 10,939 # maximum
   477,010 ft min (1.376 x 10^{-2} #/ft) = 6,564 # minimum

TABLE I

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Temp. °R	Enthalpy of Normal H_2 800 psia or 54.4 ΔTM				ΔH_n	Para Shift			ΔT_p	N_2 at 20 ATM ΔH of Several					$\frac{\# N_2}{\# H_2}$	
T	H of H_2 1932 Cambr.	H of H_2 NBS RFT	H Average	Total ΔH	Incrim-ental ΔH	% Ortho At Eq.	ΔH Conver.	ΔH for Shift	Addit. ΔT p Shift	ΔH BTU/ Mole	ΔH BTU/ #	$2\frac{\# N_2}{\# H_2}$	4	5	6	7
40	146	144	144	0	0	0	304	0	0							
50	157	162	162	15	15	2		6	1							
60	196	203	203	55	40	6		18	4							
70	242	242	242	97	42	12		36	6							
80	284	292	292	143	46.	16		54	9							
90	329	333	333	186	43	23		72	12							
100	373	381	381	232	46	28		85	16							
110	415	416	416	271	39	35		106	18							
120				310	39	42	304	127	21							
130	494	493	493	348	38	47	303	143	25							
140				385	37	53	306	161	29	0	0	0	0	0	0	
150	569	560	565	420	35	57	298	176	34	25	.89					6.
160				452	42	60	295	177	39							
180	648	650	649	504	42	62	290	180	50	640	22.8	45.6	91.2	114	137	1
200	708	710	709	564	60	64	260	166	58	930	33	66	132	165	198	2
220	778	782	782	637	73	65	240	156	59	1080 2520	38.5 90	77 180	154 360	193 450	231 540	2 6
240	838	828	833	689	52	66	226	145	60	2880	103	206	412	515	618	72
260		891	891	747	58	67	202	135	52	3060	109	218	436	545	654	76
280		953	953	809	62	68	170	116	51	3225	115	230	460	575	690	80
300		102	1022	879	69	69	155	107	40	3420	122	244	488	610	733	85
320		1094	1094	950	72	70	130	91	20	3640	128	256	512	640	768	89
340		1152	1152	1008	58	70½	110	78	18	3720	133	266	532	665	798	93
360		1220	1220	1076	54	71	95	67	18	3870	138	276	552	690	828	96
380		1274	1274	1138	46	71½	80	57		3980	142	284	568	710	852	99
400		1340	1340	1196	66	72	75	56		4180	149	298	592	740	888	103
450										4515	161	322	644	805	966	112
500										4850	173	346	692	865	1038	121

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TABLE I

	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
at 20 ATM ΔH of Several $\frac{\#N_2}{\#H_2}$								ΔH Para	4			5			6			With Para Shift 4		
H J/ le	ΔH BTU/ #	$2\frac{\#N_2}{\#H_2}$	4	5	6	7	8		ΔT	Incrimental UA_1	Total UA_2	ΔT	UA_1	UA_2	ΔT	UA_1	UA_2	ΔT	UA_1	UA_2
									100			100			100			100		
								21	104	.144		104	.144		104	.144		105	.143	
								73	102	.392	.536	102	.392	.536	101	.396	.540	106	.377	.520
								133	112	.375	.911	103	.408	.944	98	.429	.969	118	.356	.876
								197	129	.357	1.268	112	.411	1.355	103	.447	1.415	138	.333	1.209
								258	130	.330	1.600	123	.350	1.704	107	.402	1.817	142	.303	1.512
								322	120	.383	1.982	120	.383	2.088	120	.383	2.201	136	.338	1.850
								383	110	.355	2.337	110	.355	2.442	110	.355	2.555	128	.305	2.155
								437	100	.390	2.727	100	.390	2.832	100	.390	2.945	121	.322	2.477
								500	90	.422	3.149	90	.422	3.254	90	.422	3.367	115	.330	2.808
0	0	0	0	0	0	0	0	546	88	.420	3.569	80	.463	3.717	80	.462	3.830	117	.316	3.124
25	.89					6.23	7.12	596	98	.357	3.926	70	.500	4.217	70	.500	4.330	132	.265	3.389
								629	108	.389	4.315	60	.700	4.917	60	.700	5.030	147	.286	3.6750
540	22.8	45.6	91.2	114	137	166	182	684	300° 130	.224 .323	4539 4.638	57	.737	5.654	40	1.050	6.080	300° 180	.163 .233	3.838 3.908
930	33	66	132	165	198	231	264	730	175	.343	4.981	68	.882	6.536	24	2.500	8.580	228	.263	4.171
080 520	38.5 90	77 180	154 360	193 450	231 540	270 630	308 720	793	220	.331	5.313	300° 93	.524 .785	7.060 7.321	30	2.433	11.013	279	.262	4.433
880	103	206	412	515	618	721	824	834	258	.208	5.521	120	433	7.755	37	1.405	12.418	318	.164	4.597
060	109	218	436	545	654	763	872	882	500°	.011	5.532	142	.408	8.163	300° 44	.932 1.523	13.350 13.737	500	.009	4.606
3225	115	230	460	575	690	805	920	925				171	.363	8.5255	67	.925	14.662			
3420	122	244	488	610	733	854	976	985				500°	.275	8.800	95	.726	15.388			
3640	128	256	512	640	768	896	1024	1041							122	.590	15.979			
3720	133	266	532	665	798	931	1064	1086							141	.411	16.390			
3870	138	276	552	690	828	966	1104	1143							500°	.213	16.603			
3980	142	284	568	710	852	994	1136	1187												
4180	149	298	592	740	888	1036	1184	1257												
4515	161	322	644	805	966	1127	1288													
4850	173	346	692	865	1038	1211	1384													

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TABLE I CONTINUED

1	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
Temp. °R	With Para Shift 5			With Para Shift 6			With Para Shift 7			N_2 At Critical Conditions (33.5 AM)							No Shift 10 ATM 5#/#		
T	ΔT	UA_1	UA_2	ΔT	UA_1	UA_2	ΔT	UA_1	UA_2	ΔH BTU	2	4	5	6	7	8	ΔT	UA_1	UA_2
40	100			100			100										100		
50	105	.142		105	.142		105	.142									100	.150	
60	106	.377	.520	105	.381	.524	100	.4	.543								104	.385	.535
70	109	.385	.906	105	.400	.924	100	.42	.963								110	.382	.916
80	121	.380	1.286	112	.411	1.335	100	.46	1.423								108	.426	1.342
90	135	.319	1.604	119	.361	1.696	117	.367	1.790								98	.439	1.781
100	136	.338	1.942	136	.338	2.034	114	.404	2.194								88	.523	2.304
110	128	.305	2.247	128	.305	2.339	128	.305	2.499								78	.500	2.804
120	121	.322	2.569	121	.322	2.661	122	.319	2.818								65	.600	3.404
130	115	.330	2.900	115	.330	2.992	116	.328	3.415								58	.655	4.059
140	109	.339	3.239	109	.339	3.331	110	.336	3.482	0							48	.771	4.830
150	104	.356	3.595	104	.337	3.667	104	.337	3.819	6.5	13	26	32.5	39	455	52	38	.921	5.751
160	99	.424	4.019	99	.424	4.091	99	.424	4.242	11	22	44	55	66	77	88	28	1.500	7.251
180	107	.393	4.41180	90	.467	4.558	90	.467	4.710	21	42	84	105	126	147	168	39	1.177	8.327
200	116	.517	4.929	82	.732	5.290	86	.698	5.407	33	66	132	165	198	231	264	62	.968	9.296
220	300° 152	.196 .480	5,125 5.409	89	.820	6.110	40	1.725	7.232	48	96	192	240	288	336	384	300°	.517	9.812
240	180	.289	5.698	97	.536	6.6463	53	.981	8.213	230° 93	180 186	360 372	450 466	540 558	630 651	720 774			
260	194	.299	5.997	300° 96	.1366 .604	6.783 6.707	50	1.160	9.373	103	206	412	515	618	721	824			
280	222	.279	6.276	118	.525	7.232	52	1.192	10.566	111	222	444	555	666	777	888			
300	500°	.229	6.505	135	.511	7.743	300° 55	.773 1.254	11,340 11.820	118	236	472	590	708	826	944	50 ATM 6# / .		
320				142	.507	8.250	64	1.225	12.945	124	248	496	620	744	868	992	BTU	$\overline{\Delta T}$	UA_1
340				159	.365	8.615	77	.753	13.698	130	260	520	650	780	910	1040	400	100	4.000
360				500°	.190	8.806	89	.607	14.305	135	270	540	675	810	945	1080	100	80	1.250
380							97	.474	14.779	141	282	564	705	846	987	1128	100	70	1.429
400							500°	.6896	15.469								75	60	1.250
450																	50 ATM 5# N_2/		
500																	560	104	5.30

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	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59		
ons (33.5 AM)				No Shift 10 ATM 5#/#			No Shift 5 ATM 5#/#			With Para Shift 2 ATM 5#/#			With Para Shift 5 ATM 5#/#			With Para Shift 2ATM 6#/#	
	6	7	8	ΔT	UA_1	UA_2	ΔT	UA_1	UA_2	ΔT	UA_1	UA_2				ΔT	UA_2
				100			100			100			100			100	
				100	.150		100	.150		100	.150		101	.149		101	.148
				104	.385	.535	104	.385	.5346	100	.40	.550	108	.370	.519	101	.545
				110	.382	.916	100	.420	.955	94	.426	.976	106	.396	.915	94	.991
				108	.426	1.342	90	.511	1.465	87	.529	1.504	99	.465	1.380	86	1.526
				98	.439	1.781	80	.538	2.003	79	.544	2.049	92	.467	1.847	79	2.071
				88	.523	2.304	70	.657	2.660	72	.639	2.687	86	.535	2.382	73	2.701
				78	.500	2.804	60	.650	3.310	65	.600	3.287	78	.500	2.882	66	3.292
				65	.600	3.404	50	.780	4.090	58	.672	3.960	71	.549	3.431	59	3.952
				58	.655	4.059	40	.950	5.040	53	.717	4.677	65	.585	4.016	53	4.670
				48	.771	4.830	30	1.233	6.274	48	.771	5.448	59	.627	4.643	47	5.457
5	39	455	52	38	.921	5.751	20	1.750	8.023	41	.854	6.301	54	.648	5.291	42	6.290
	66	77	88	28	1.500	7.251	1.0	4.200	12.223	39	1.176	7.378	49	.857	6.149	37	7.425
	126	147	168	39	1.177	8.327	20	2.100	14.323	70	.600	7.978	70	.600	6.749	27	8.980
	198	231	264	62	.968	9.296	52	1.54	15.478	105	.571	8.550	110	.545	7.294	36	10.647
)	288	336	384	300°	.517	9.812	80	.913	16.390	300° 140	.521 .521	9.071 9.071	139	.525	7.819	58	11.906
)	540	630	720				300°	0	16.390				300°	.525	7.819	70	12.649
5	558	651	774														
)	618	721	824													94	13.266
5	666	777	888													300°	13.307
0	708	826	944	50 ATM 6#/#													
0	744	868	992	BTU	$\overline{\Delta T}$	UA_1	UA_2										
0	780	910	1040	400	100	4.000											
5	810	945	1080	100	80	1.250	5.250										
5	846	987	1128	100	70	1.429	6.679										
				75	60	1.250	7.928										
				50 ATM 5# N_2/# H_2													
				560	104	5.30	5.30										

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TABLE I CONTINUED

	60	61	62	63	64	65	66	67	68	69	70	71	72	73
6 #/#	ATM Press.	B. P. T Const	H_1	H_2	$6XH_1$	$6XH_2$	H 220	6X	H 240	6X	H 270	6X	H 300	300
	1	140	85	0	510	0	107	642	112	672	119.5	717	126.6	759
	2	158	87	8	522	48	106.5	639	111.5	669			126.0	756
	5	170	90.5	15	543	90	105	630	111	666			125.3	752
	10	188	90.8	25	545	[illegible]	102	612	109	654	116.5	699	124.2	745.2
	20	210	88	38.5	528	231	93	558	103	618			121.6	730
	30	220	83	51	498	306			96	576			119	714
	33.5	228	77	57	562	342			93	558	106.5	639	117	702
	50						43.8	263	64.8	389	96.7	580	112.5	675
5 #/#	ATM Press				$5XH_1$	$5XH_2$	H 220	5X	H 240	5 X	H 270	5 X	H 300	5 X
	1	140	85	0	425	0	107	535	112	560	119.5	598	126.6	633
	2	158	87	8	435	40	106.5	533	111.5	555.25			126.0	630
	5	170	90.5	15	452.5	75	105	525	111	556			125.3	627
	10	188	90.8	25	454	125	102	510	109	545	116.5	583	124.2	
	20	210	88	38.5	440	192.5	93	465	103	515	112	560	121.6	608
	30	220	83	51	415	255			96	480			119	595
	33.5	228	77	57	385	285			93	465	106.5	532.5	117	585
	50						43.8	219-	64.8	324	96.7	484	112.5	563
	ATM Press	200	5 X	6 X	180	5 X	6 X							
	1	101.2	506	607	96.8	484	581							
	2	100.8	504	605	96.2	481	577							
	5	99	495	594	93	465	558							
	10	96	480	576										

TABLE I CONTINUED

1	5	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	
h H_2		Δ H h − p	$\Delta H_{40}=0$	800 psia Para	Addit. ΔT	No Para-Ortho Shift 4			No Para-Ortho Shift 5			No Para-Ortho Shift 6			With Para S 4		
40	0			0													
50	15	228.15		15	0												
60	55			55	0												
70	97	228.15		97	0												
80	143			143	0												
90	186			186	0												
100	232			232	0												
110	271			271	0												
120	310			310	0												
130	348	228.15	0	348	0				90	.422	3.254						
140	385	228	.15	385	0				80	.463	3.717						
150	420	226.5	1.65	421	0	98	.357	3.926	70	.500	4.217	70	.500	4.330	132	.265	3
160	452	219.4	8.75	460	3	111	.378	4.304	63	.667	4.883	63	.667	4.997	150	.280	3
180	504	208.5	19.65	524	6	300° 136	.215 .309	4.520 4.614	63	.667	5.550	46	.913	5.910	300° 186	.158 .223	3 3
200	564	194.25	33.90	598	12	187	.321	4.934	80	.750	6.300	36	1.667	7.576	240	.250	4
220	637	180.75	47.40	684	15	235	.3106	5.245	300° 108	.453 .676	6.754 6.976	45	1.622	9.199	294	.248	4
240	689	165.75	62.40	751	18	276	.188	5.433	138	.377	7.353	52	1.000	10.198	336	.155	4
260	747	149.0	79.15	826	22	278	.011	5.444	164	.354	7.707	300° 66	.788 .939	10.987 11.138	500°	.008	4
280	809	131.25	96.90	906	25				196	.316	8.023	92	.783	11.921			
300	878	115.5	112.65	991	29				500°	.241	8.264	124	.556	12.477			
320	950	97.5	130.65	1081	30							152	.474	12.951			
340	1008	84.3	143.85	1152	36							177	.328	13.2786			
360	1076	71.25	156.90	1233	41							500°	.169	13.448			
380	1130	60.	168.15	1298	44												

TABLE I CONTINUED

82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98
Ortho Shift 5		No Para-Ortho Shift 6			With Para Shift 4			With Para Shift 5			With Para Shift 6			With Para Shift 7		
.422	3.254															
.463	3.717							109	.339	3.239						
.500	4.217	70	.500	4.330	132	.265	3.389	104	.336	3.576	104	.337	3.667	104	.337	3.818
.667	4.883	63	.667	4.997	150	.280	3.669	102	.4117	3.988	102	.411	4.079	102	.411	4.230
.667	5.550	46	.913	5.910	300°	.158	3.828	113	.372	4.359	96	.438	4.517	96	.437	4.668
					186	.223	3.896									
.750	6.300	36	1.667	7.576	240	.250	4.145	128	.469	4.828	94	.638	5.155	98	.612	5.280
.453	6.754	45	1.622	9.199	294	.248	4.394	300°	.179	5.007	104	.702	5.856	55	1.327	6.607
.676	6.976							167	.437	5.265						
.377	7.353	52	1.000	10.198	336	.155	4.548	198	.262	5.528	115	.452	6.309	68	.765	7.372
.354	7.707	300°	.788	10.987	500°	.008	4.558	216	.268	5.796	300°	.353	6.663	74	.784	8.155
		66	.939	11.138							118	.492	6.800			
.316	8.023	92	.783	11.921				247	.251	6.0472	143	.434	7.234	300°	.547	8.702
														80	.775	8.931
.241	8.264	124	.556	12.477				500°	.205	6.253	164	.421	7.655	93	.742	9.673
		152	.474	12.951							172	.419	8.703	107	.673	10.346
		177	.328	13.2786							195	.297	8.370	115	.504	10.850
		500°	.169	13.448							500°	.156	8.528	138	.391	11.241
														500°	.500	11.7[illegible]1

TABLE I CONTINUED

# N_2/ # H_2	Normal UA_{n_e}	Equilibrium UA_{n_e}	ΔUA	% Increase			UA_p	UA_{p_e}	ΔU_A	% Increase	
				$\Delta UA/UA_n$	$\Delta UA/UA_{n_e}$					$\Delta UA/UA_p$	$\Delta UA/UA_{p_e}$
4	4.539	3.838	.701	18.26	15.44		4.520	3.83	0.69	18.0	15.27
5	7.06	5.125	1.935	37.76	27.41		6.754	5.007	1.747	34.89	25.87
6	13.35	6.78	6.57	96.90	49.21		10.987	6.663	4.324	64.89	39.36
7	very * large	11.34									
4	5.532	4.606	.926	20.10	16.74						
5	8.800	6.51	2.29	35.18	26.02						
6	16.603	8.80	7.803	88.67	47.00						
7	very * large	15.47									

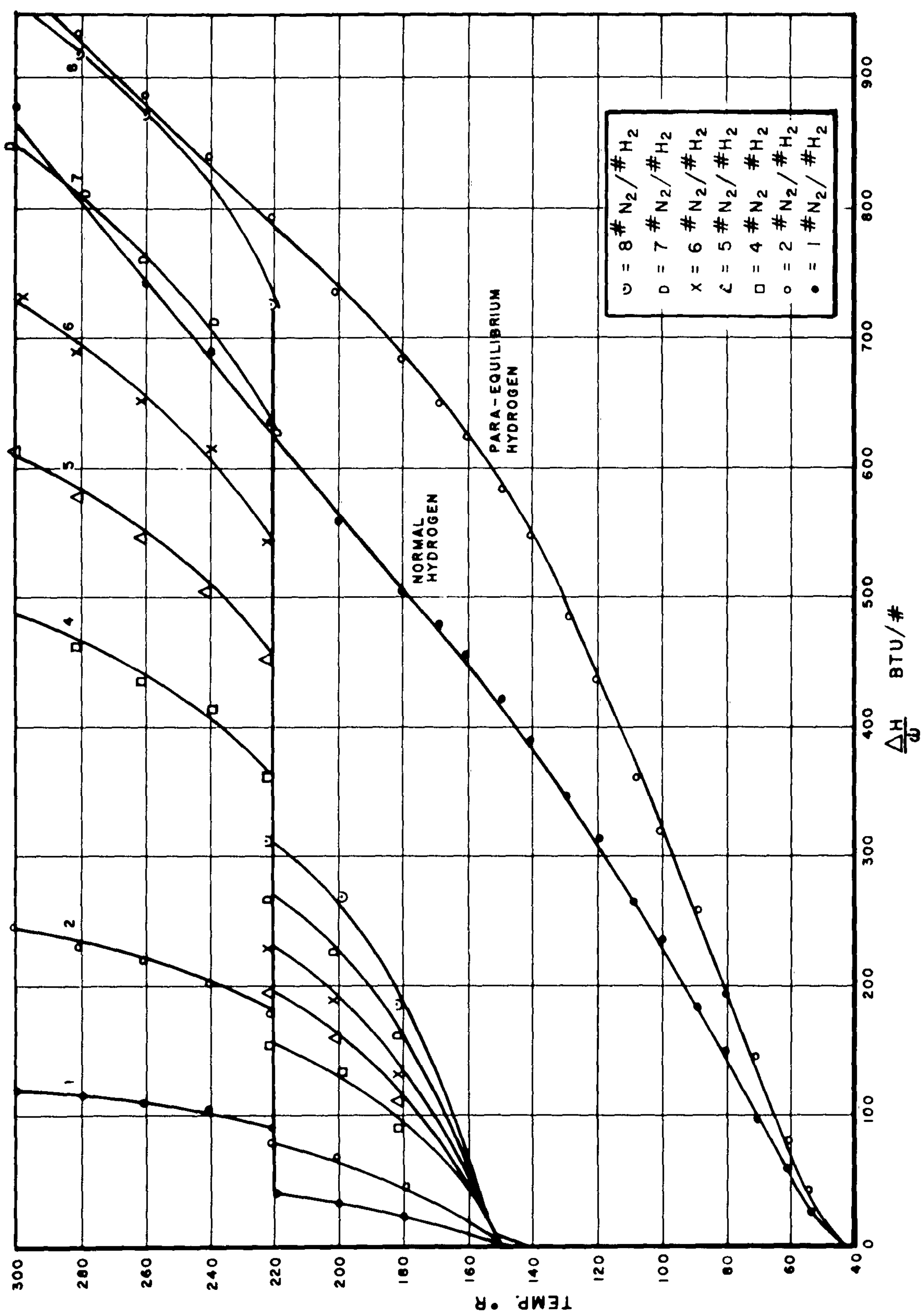

Figure 1. Nitrogen-Hydrogen Heat Exchange at 20 ATM N_2 Pressure and 800 PSIA H_2 Pressure, 40° to 300° R.

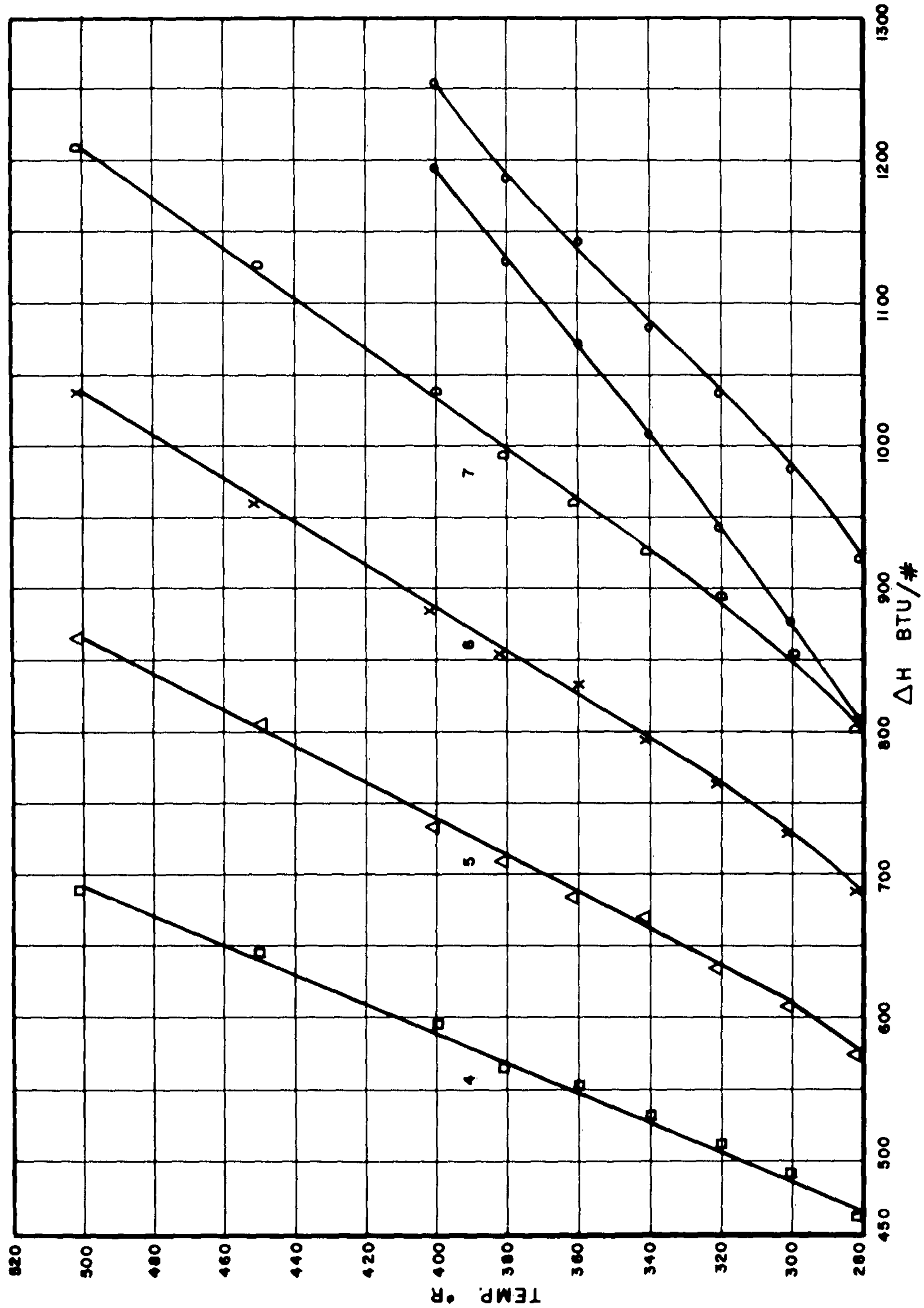

Figure 2. Nitrogen-Hydrogen Heat Exchange at 20 ATM N_2 Pressure and 800 PSIA H_2 Pressure, 280° to 520° R.

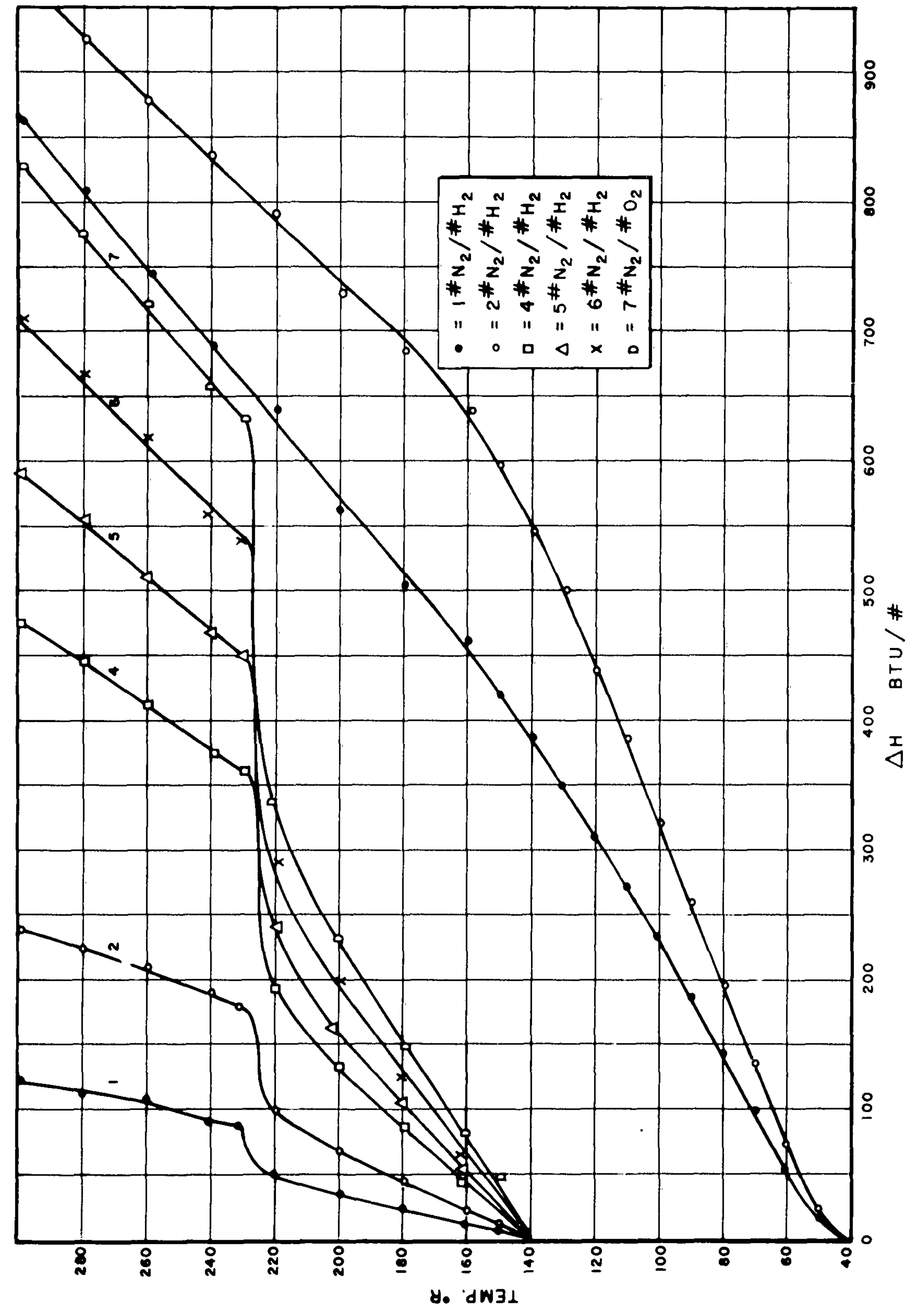

Figure 3. Nitrogen-Hydrogen Heat Exchange - N_2 at 33.5 ATM (Critical), H_2 at 800 PSIA.

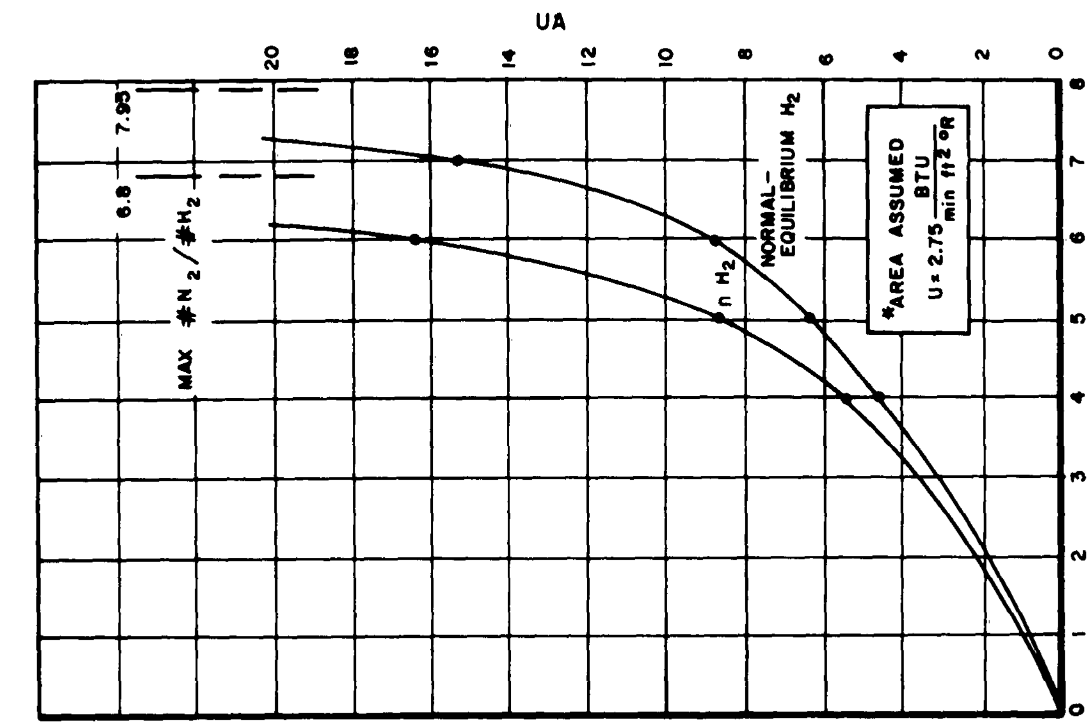

Figure 5. Nitrogen-Hydrogen Heat Exchange--
20 ATM N_2 from 500° to 140°R with H_2 at 800 PSIA.

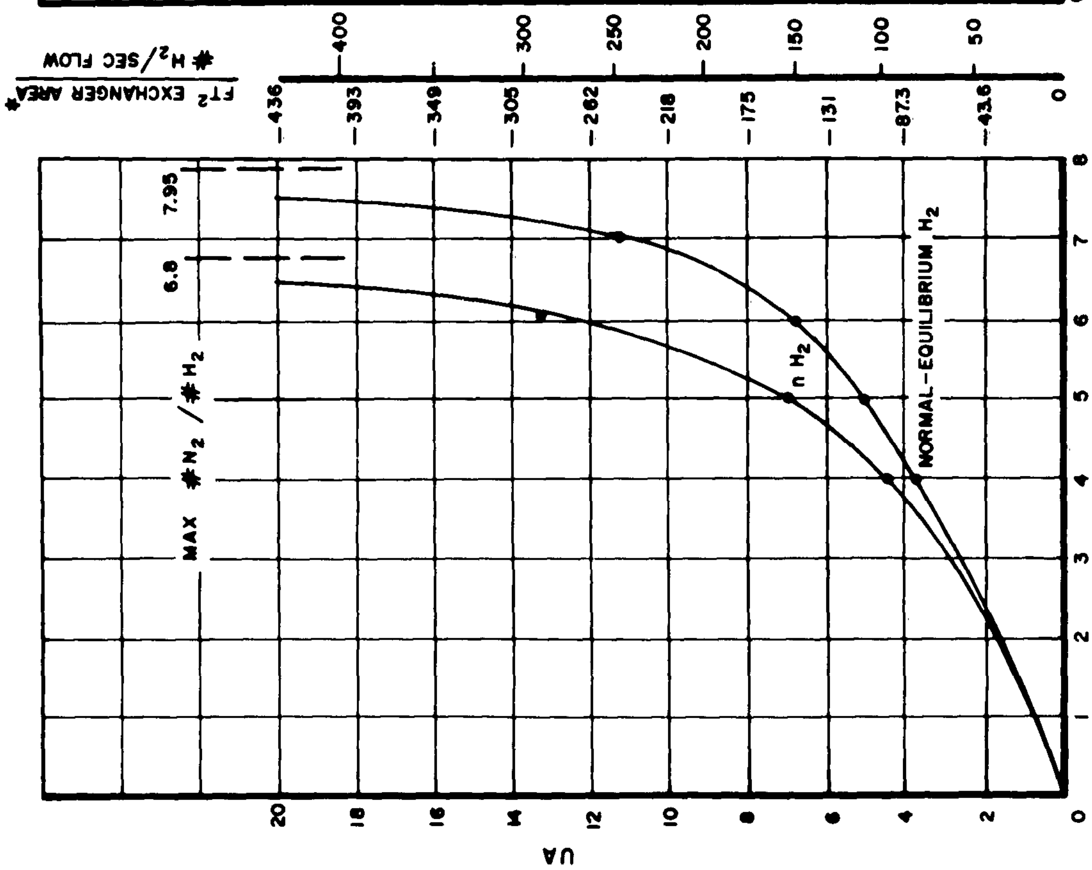

Figure 4. Nitrogen-Hydrogen Heat Exchange--
20 ATM N_2 at 300° to 140°R with H_2 at 800 PSIA.

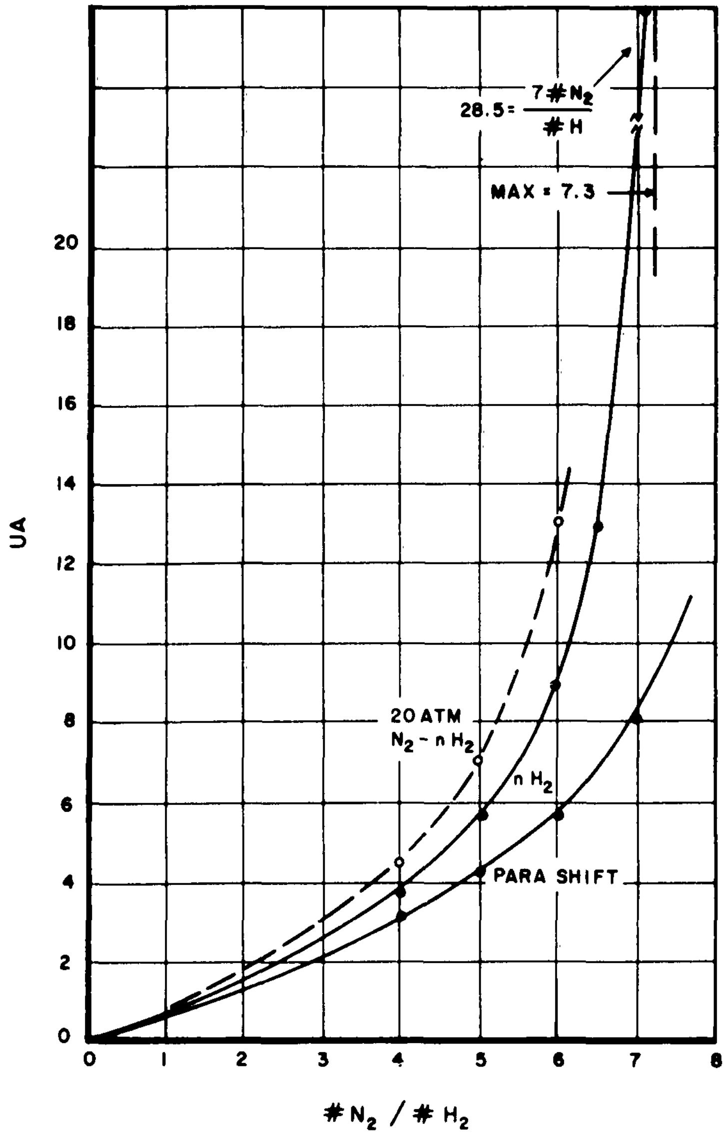

Figure 6. Estimated Nitrogen-Hydrogen Heat Exchange-- 33.5 ATM N_2 from 300° to 140° R with H_2 at 800 PSIA.

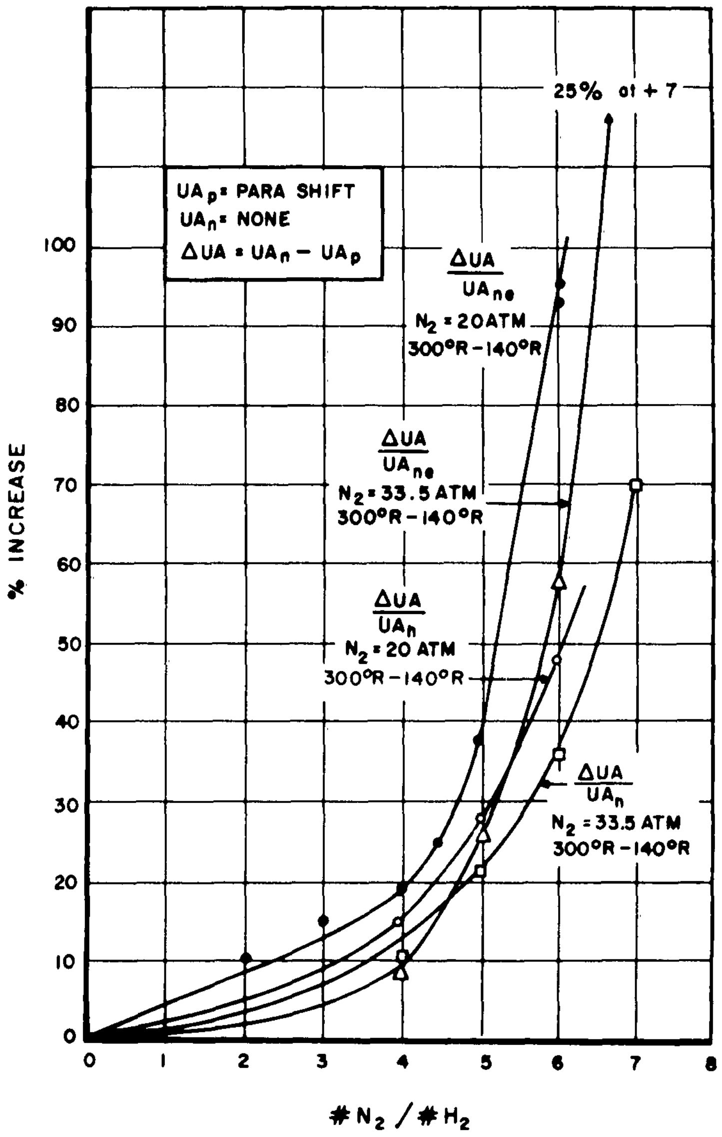

Figure 7. Per Cent Increase in Size and weight of Exchanger When No Para-Ortho Shift Takes Place.

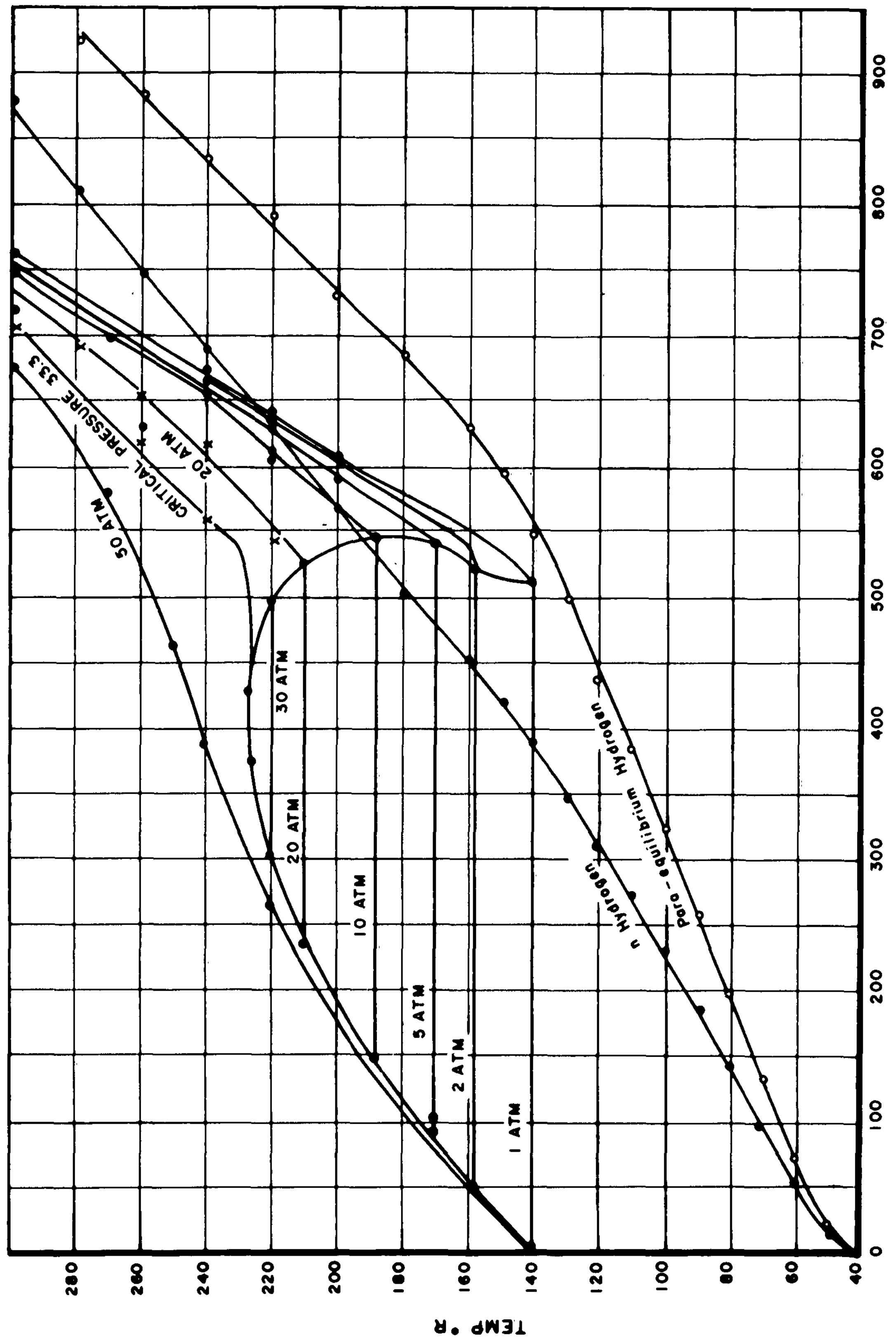

Figure 8. Nitrogen-Hydrogen Heat Exchange for 6 $\#N_2/\#H_2$ at 1 to 50 ATM N_2 and 800 PSIA H_2.

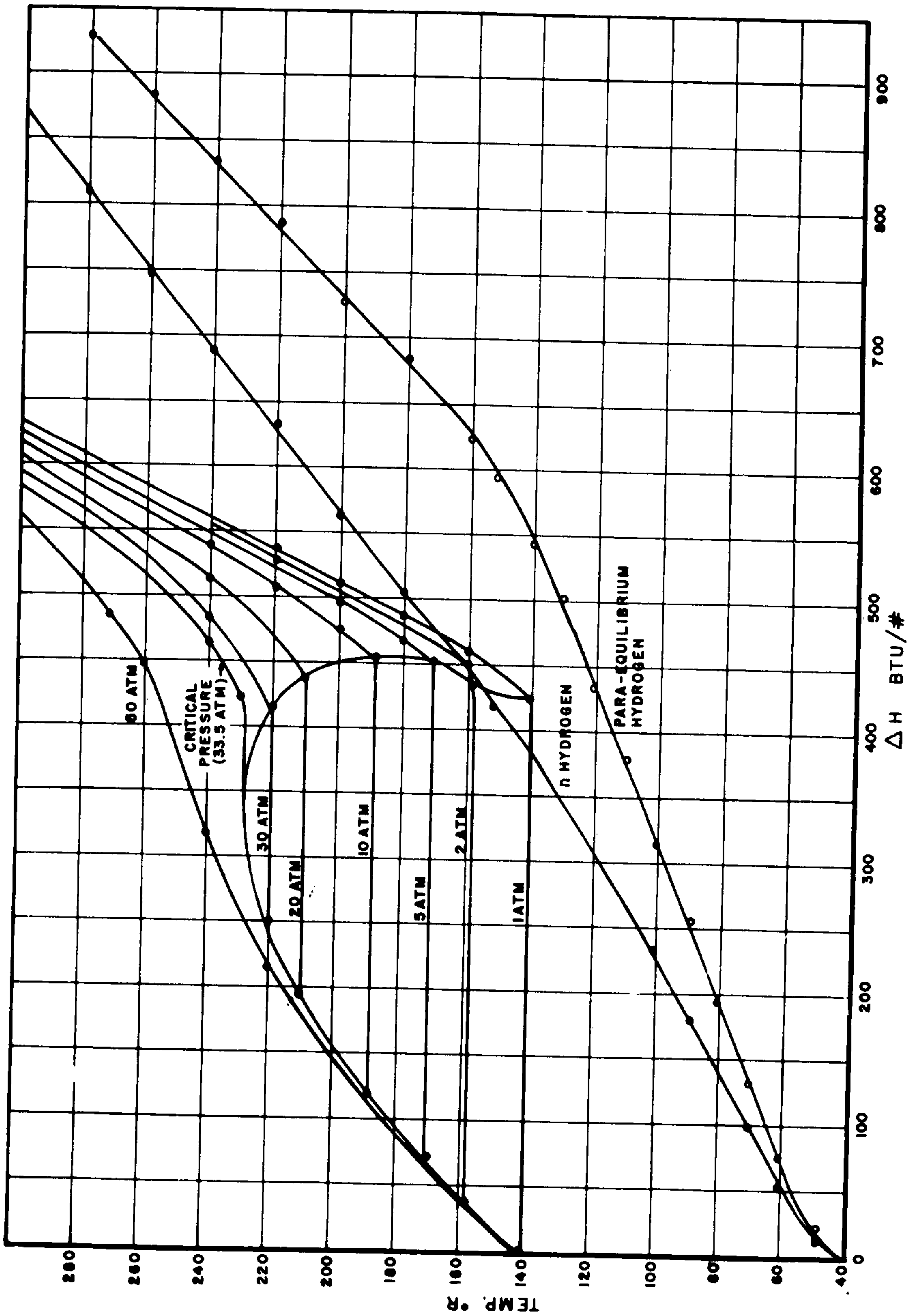

Figure 9. Nitrogen-Hydrogen Heat Exchange for 5 $\#N_2/\#H_2$ at 1 to 50 ATM N_2 Pressure and 800 PSIA H_2.

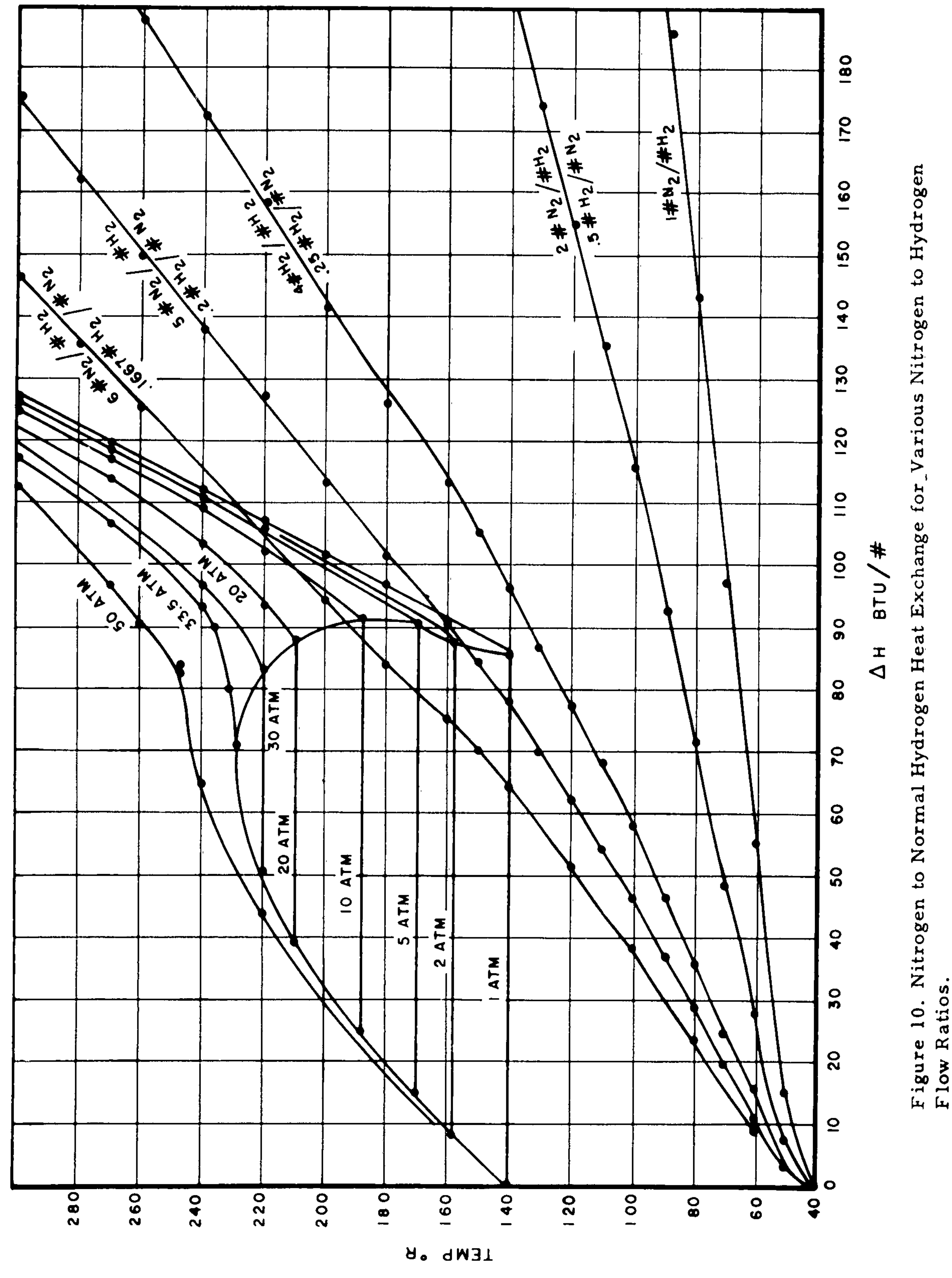

Figure 10. Nitrogen to Normal Hydrogen Heat Exchange for Various Nitrogen to Hydrogen Flow Ratios.

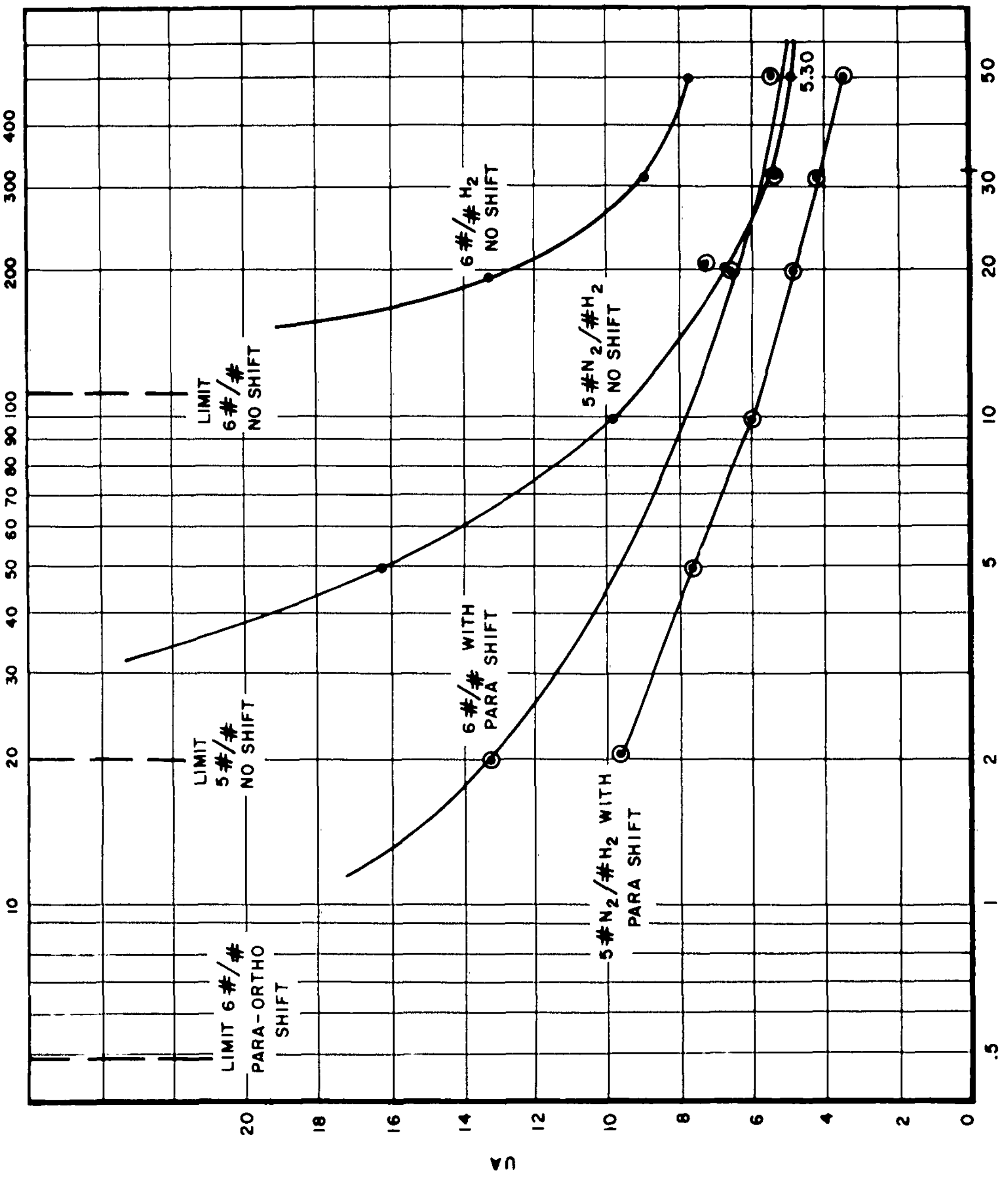

Figure 11. Effect of N_2 Pressure on UA in Exchanger Design.

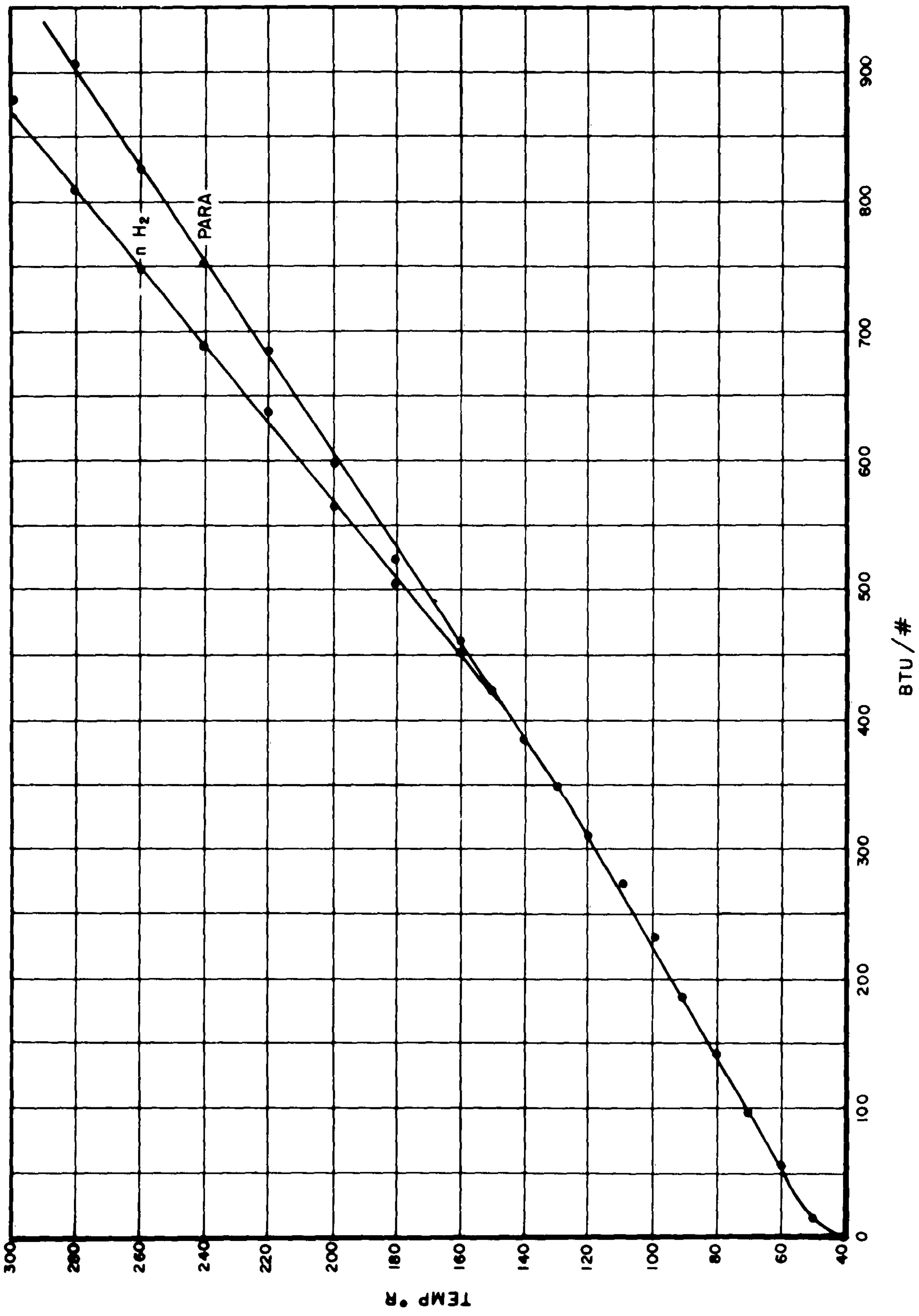

Figure 12. Calculated Enthalpy of Para Hydrogen at 800 PSIA from Normal Hydrogen Data-- 40° to 300° R.

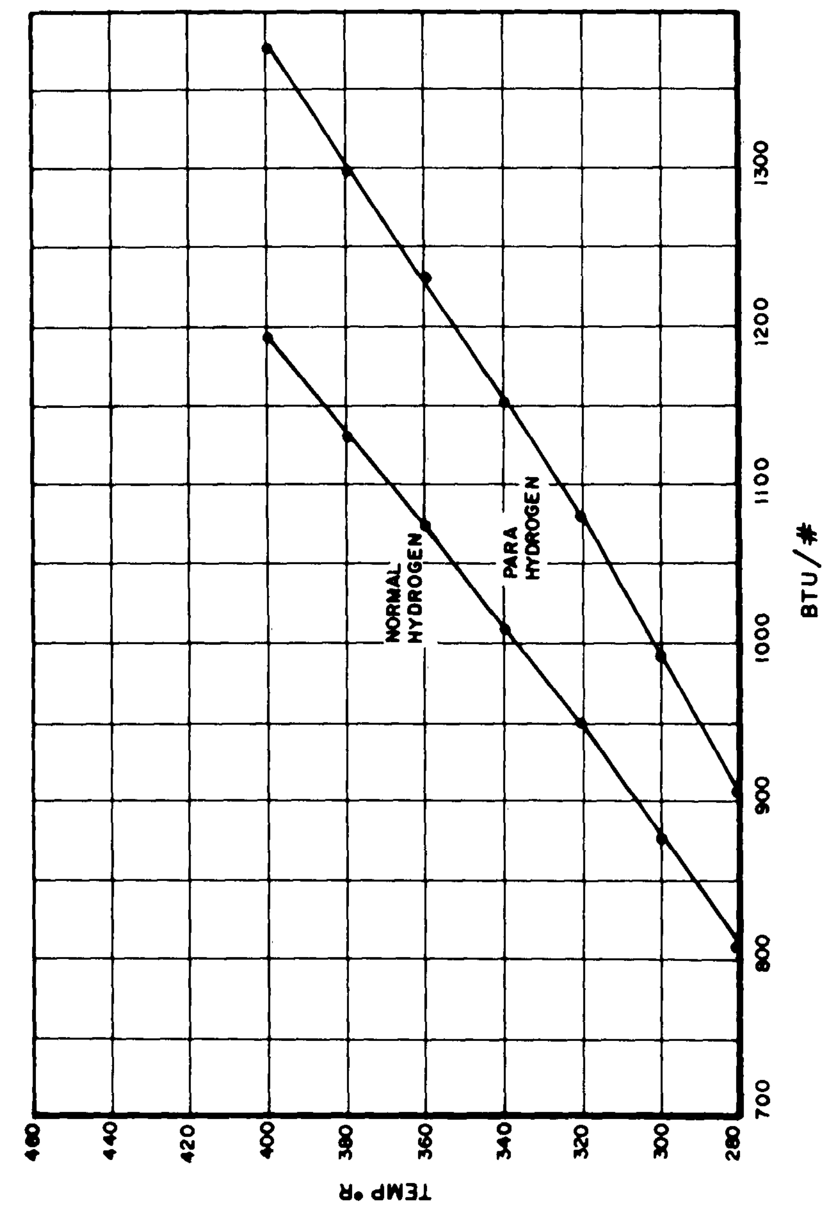

Figure 13. Calculated Enthalpy of Para Hydrogen at 800 PSIA from Normal Hydrogen--280° to 400°R.

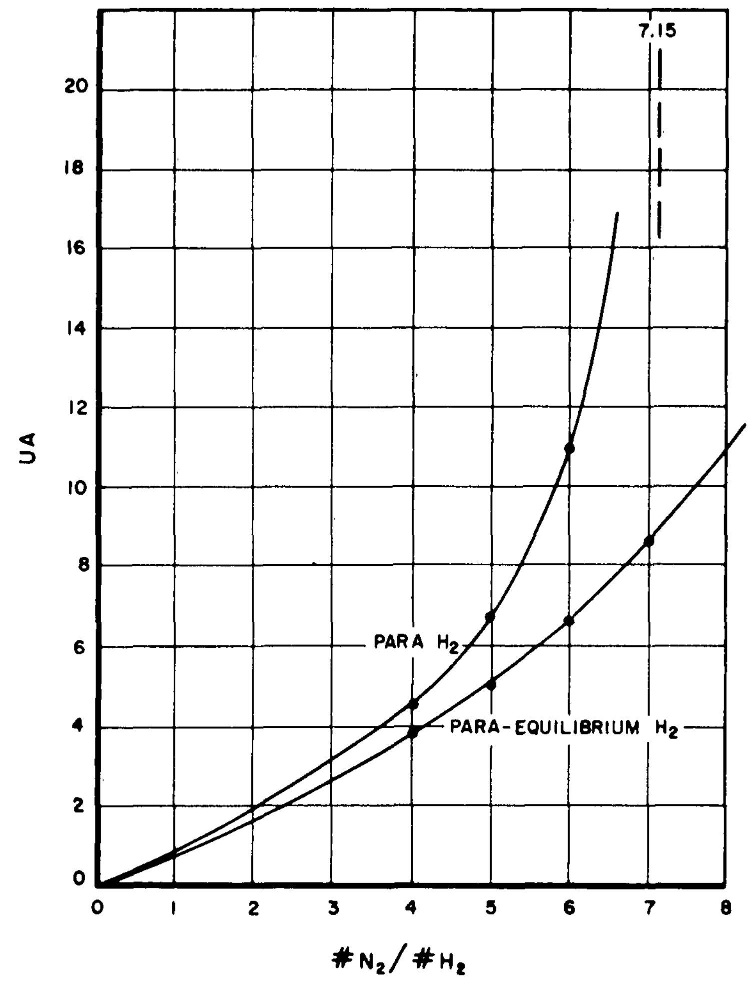

Figure 14. Nitrogen-Hydrogen Heat Exchange--
20 ATM N_2 from 300 ° to 140°R with 800 PSIA H_2.

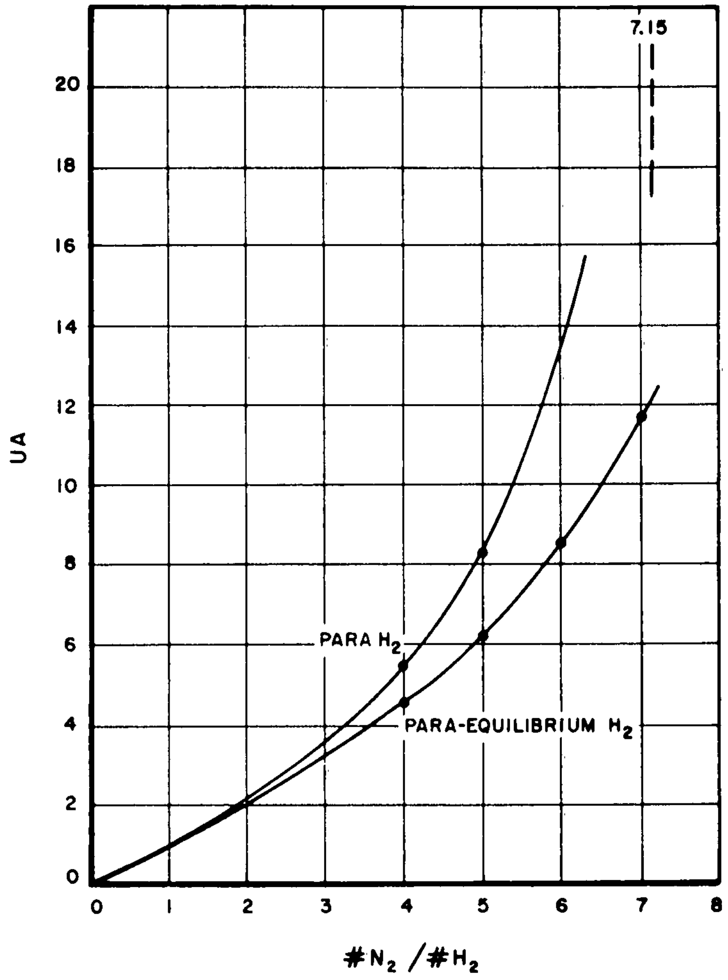

Figure 15. Nitrogen-Hydrogen Heat Exchange-- 20 ATM N_2 from 500 ° to 140°R with 800 PSIA H_2.

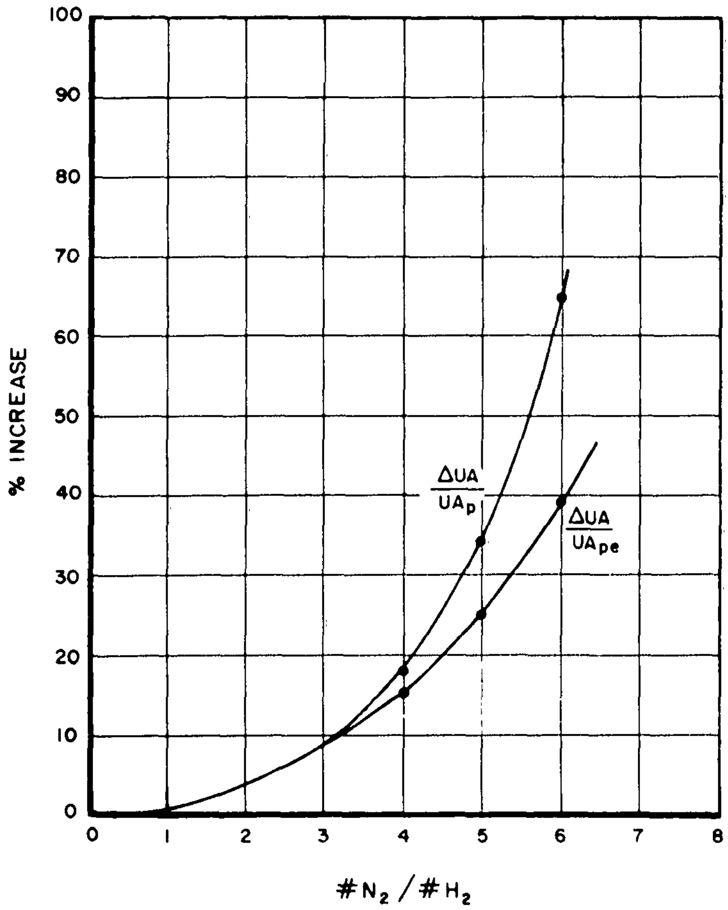

Figure 16. Per Cent Increase in Weight if No Para-Ortho Shift Takes Place.

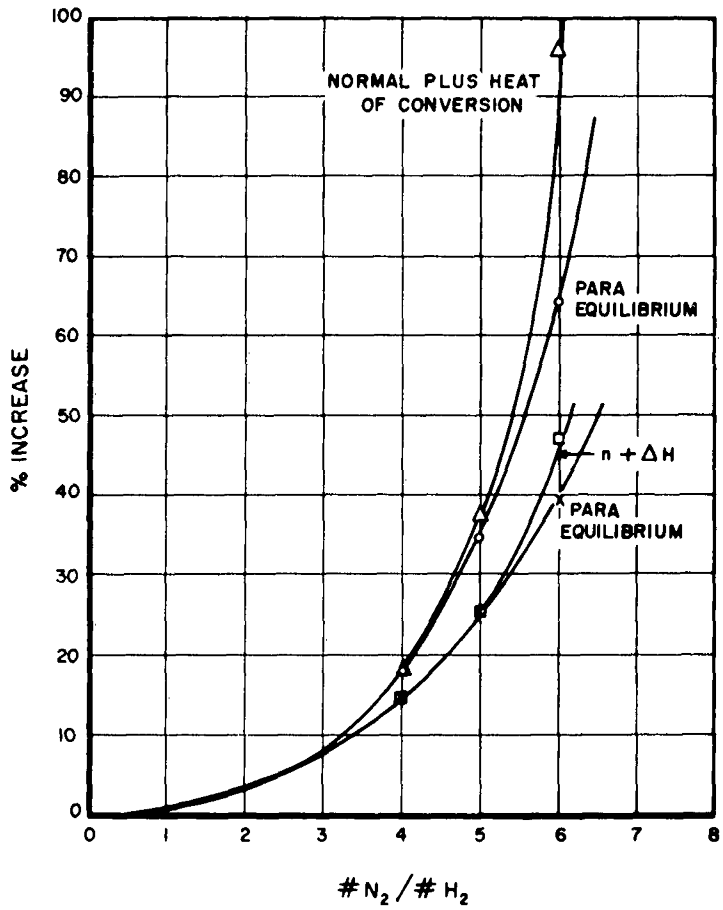

Figure 17. Difference Between Normal Hydrogen Plus Heat of Conversion and Para-Equilibrium Type Calculation for Increase in UA.

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THE EFFECT OF PARA-ORTHO SHIFT ON HEAT EXCHANGER DESIGN IN HYDROGEN NITROGEN HEAT EXCHANGE AT HIGH PRESSURES, by James H. L. Lawler. December 1960. 32 p. Incl. illus. & tables. (Project 3048) WADD TN 60-238) Unclassified report.

The effect of para-ortho shift is found on heat exchanger design by calculating heat exchanger sizes for several hydrogen to nitrogen flow ratios. This calculation shows that size is exponential to a limit when plotted against lbs of H_2/lbs of N_2

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